GPR ground-wave parameters changes due to variation of soil moisture

Henryk Marcak[1], *Sylwia* Tomecka-Suchoń[1], *Rafał* Czarny[2,*], *Paweł* Pysz[1], *Akinniyi* Akinsunmade[3], and *Tetiana* Kril[4]

[1]AGH, University of Science and Technology, Kraków, Poland
[2]MEERI PAS, Department of Geoengineering and Environmental Engineering, Kraków, Poland
[3]Nigerian Geological Survey Agency, Nigeria
[4]NAS, Institute of Geological Sciences, Kyiv, Ukraine

Abstract. The soil moisture distribution is important in terms of assessment of agricultural conditions for plant cultivations. The aim of this study is to develop methodology for monitoring soil moisture by the use of gound-penerating radar (GPR). This non-invasive geophysical method has been widely introduced for this purpose for the last decade. However, there is still lack of routinly application in agriculture. The main reasons are time-consuming data processing and aqusition, particulary for multi-offset measurments. In order to fill this gap we tried to adapt single-offset measurment. Our field study contained several measurments for different time span after ground irrigation. We used 800 MHz shielded and 200 MHz unshelded antennas. We focused on ground wave which propagates just beneath the surface. We observed relative velocity and amplitude spectrum changes of air and ground waves after water irrigation. These changes has an explanation in electromagnetic wave propagation theory. Water irrigation causes the increase of ground wave time arrivals and shift of amplitude spectrum towards lower frequencies.

Keywords: ground penetrating radar, GPR ground-wave, soil moisture, soil water content

1 Introduction

Obtaining information about the spatial and temporal distribution of water in ground is important for precision agricultural programs. Nowadays, the most common electromagnetic method for the soil water content estimation is TDR (time-domain reflectometry) [10]. However, this method can monitor water content at one location, therefore it is difficult and expensive to apply for wide range areas. This technical gap can be fulfilled by non-invasive GPR method which allows to probe soil water content from any area with high resolution.

GPR has made significant progress for last 25 years in water content estimation [8]. A various methodologies have been introduced and summarized by Huisman et al. [5] and by

* Corresponding author: czarny@min-pan.krakow.pl

Klotzsche et al. [8]. Those methods are based on single- or multi-offset (called wide angle reflection and refraction – WAAR) GPR measurements which can be done at surface or in the borehole.

At the beginning of this paper, theoretical background of GPR waves parameters changes in terms of water content estimation was described. Then, case study was demonstrated. Field experiment contained GPR measurements by 800 MHz shielded and 200 MHz unshielded antennas. Measurements were carried out in two series: before and after water irrigation. Relative velocity and power spectrum density (PSD) changes were measured with reference to soil moisture. Time delays and shifts of maximum energy at PSD for GPR ground wave after water irrigation were observed.

2 Theoretical background

The most common method for assessing soil water content with use of GPR is to measure the velocity of electormagnetic waves. The velocity V depends on the relative dielectric permittivity ε_r with relation described by formula:

$$\varepsilon_r = \frac{c^2}{V^2}, \tag{1}$$

where c – free space electromagnetic wave propagation velocity (3 x 10^8 m/s). The higher values of permittivity due to e.g. water content, the lower velocity of electromagnetic waves. The apparent ε_r, i.e. permittivity determined from GPR measurment can be directly connected to volumetric soil water content by use of empirical equation introduced by Jacobsen and Schrjoning [5]:

$$\theta = 5.3\times10^{-2} + 2.97\times10^{-2}\varepsilon_r - 5.5\times10^{-4}{\varepsilon_r}^2 + 4.3\times10^{-6}{\varepsilon_r}^3. \tag{2}$$

The changes in soil water content can be aslo observed in a fequency domain. The dielectical losses due to water saturation can shift maximum amplitude spectra towards lower frequencies [1,2]. From theoretical point of view GPR waves propagation depends on complex dilectric premitivity ε^*. According to Debye [3] the dipolar response of the medium to the electrical field for single relaxation time τ can be written as:

$$\varepsilon^*(\omega) - \varepsilon_\infty \approx \frac{1}{1-i\omega\tau}, \omega_p = \frac{1}{\tau}, \tag{3}$$

where ω_p - peak loss frequency, ε_∞ - real part of $\varepsilon^*(\omega)$ at infine frequency. The consequence of electric dispersion is the dielectric loss in the medium reveals as a imaginary part of electrical permittivity:

$$\varepsilon^*(\omega) = \varepsilon' + i\varepsilon'', \tag{4}$$

where ε' and ε'' are real and imaginary permittivity, respectively. However, this description isn't useful in practice. The more general approach was proposed by Jonscher [7], where imaginary and real parts of permittivity are proportional to the frequency:

$$\varepsilon'(\omega) \approx \varepsilon''(\omega) \approx \omega^{n-1} \text{ for } \omega > \omega_p. \tag{5}$$

For this assumption for positive frequencies the following formula can be introduced [1]:

$$\varepsilon^*(\omega) = \varepsilon_r \left(\frac{\omega}{\omega_r}\right)^{n-1}\left[\sin\left(\frac{n\pi}{2}\right) + i\cos\left(\frac{n\pi}{2}\right)\right], \tag{6}$$

for 1> $n > 0$.
The complex spectrum of the electrical signal has form [1]:

$$E(\omega, z) = E_9(\omega)e^{\left[i\frac{\omega}{V(\omega)}z\right]}e^{-\alpha z} \text{ for } \alpha = \frac{\omega}{2V_0 Q}. \tag{7}$$

$E_9(\omega)$ - signal transmitted at distance z, Q - quality factor of attenuation, V_0 – phase velocity for selected frequency. Periodical part in formula (7) is relativly small and it can be assumed that the spectrum depends only on $E_9(\omega)$, V_0 and Q for a chosen frequency range. The examples of $E(\omega, z)$ for various Q, for velocity V_0 equal 10 cm/ns and $E_9(\omega)$ as a gaussian curve with maximum at 600 MHz is presented in Figure 1. The periodical component in the frequency range 400-800 MHz was neglected. Frequency as well as $E(\omega, z)$ decreases for small Q i.e. for high attenuation.

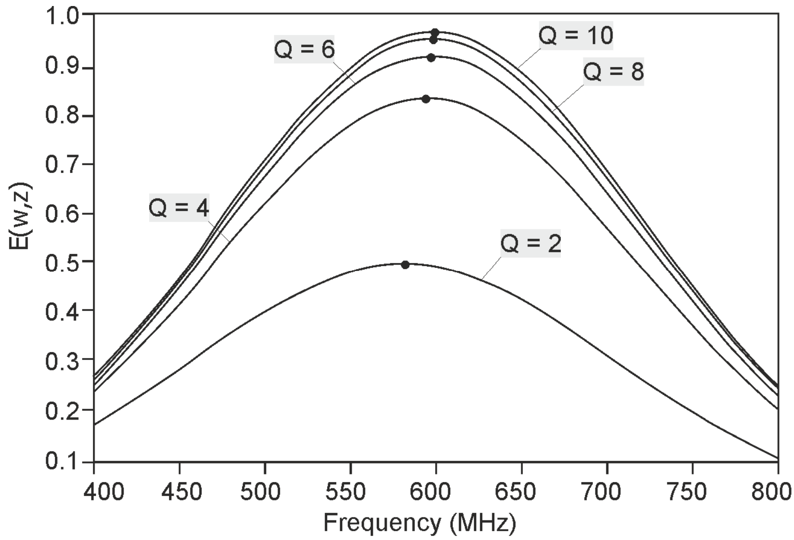

Fig. 1. The complex spectrum of the electrical signal transmitted at a distance z in the frequency range 400-800 MHz, for velocity 10 cm/nsec and $E_9(\omega)$ in the form of gaussian curve.

3 Data and methodology

The aim of case study was to observe GPR waves parameters changes due to soil moisture. In order to track these changes dozens litres of water were poured down on the surface to mimic irrigation process. GPR method was applied before and after irrigation. The area of field study was dominated by sand formation up to 5 m depth. The measurements were contained 14 standard GPR single-offset profiles by 800 MHz shielded antenna and 2 GPR profiles with multi-offset technique (WAAR) by 200 MHz unshielded antenna. All profiles had 4 m long and were carried out through the same path.

The examples of radargrams before and after irrigation for 200 MHz and 800 MHz antennas are shown in Figure 2 and 3, respectively. In order to preserve as much information from gathered data as possible, only necessary processing steps like static correction and mean amplitude subtraction were done. In Figure 3 echograms from multi-offset measurements are presented. Air and ground waves are visible. Velocity of these waves decreases for measurement about 30 minutes after water irrigation. For air wave it is reduction from about 30 to about 28 m/ns and for ground wave from about 14 to about 12 m/ns. In Figure 2 it can be seen that traces are stretched after irrigation, particularly in the canter of the profile where irrigation was the highest (Fig. 2, box with black dashed line). Moreover, radargrams before irrigation and the day after irrigation are similar. Probably, water infiltrated to the deeper layers or/and evaporated the day after.

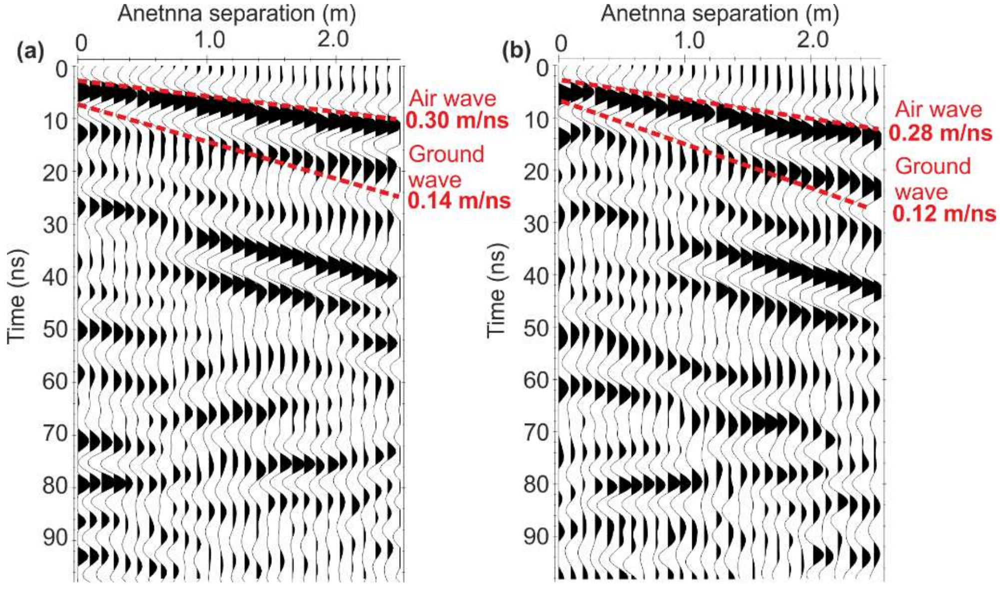

Fig. 2. Wide angle reflection and reflection (WARR) radargrams with the use of 200 MHz antenna. Velocity decreases for air and ground waves after water irrigation.

Even if WARR technique gives robust estimation of GPR waves velocity that can be transformed to volumetric water content (equation (2)), this method is time consuming, hence difficult to apply for agricultural purposes. In our study, we put much more effort to adapt single-offset GPR measurement to monitor some relative changes of GPR waves parameters. We focused on GPR ground wave acquired by 800 MHz single-offset antenna. Ground wave propagates just close to the surface, therefore it is suitable for agriculture. As described in paragraph 2 soil moisture can reduce velocity and frequency of GPR waves. Therefore, to find how the water influences velocity and frequency in our data we decided to average all traces within the single profile. It helped us to compare all the measurements. Eventually, each of 14 echograms, for different time span after irrigation, was represented by the single trace (Fig. 4). After averaging, each trace was shifted according to the time of the first maximum corresponding to GPR air wave. In Figure 4 two different time-windows are marked: for air wave and for ground wave by the use of velocities from WAAR (Fig. 2). Due to small distance between transmitter and receiver both waves overlap.

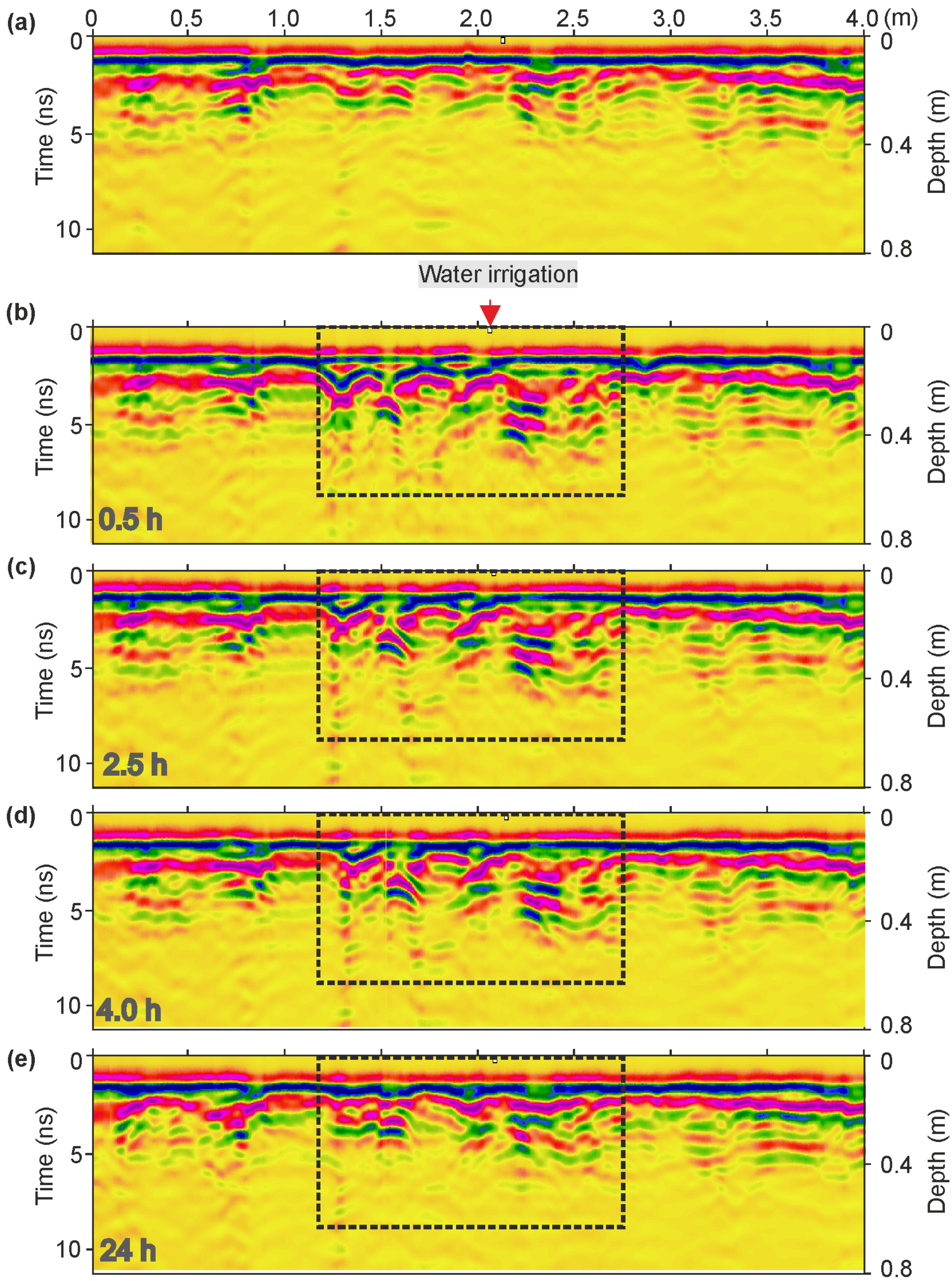

Fig. 3. Radargrams before (a) and after (b-e) water irrigation for different time span. Changes due to soil moisture are visible inside the box marked by black dashed line. Radargram after 24 h is similar to that one before water irrigation.

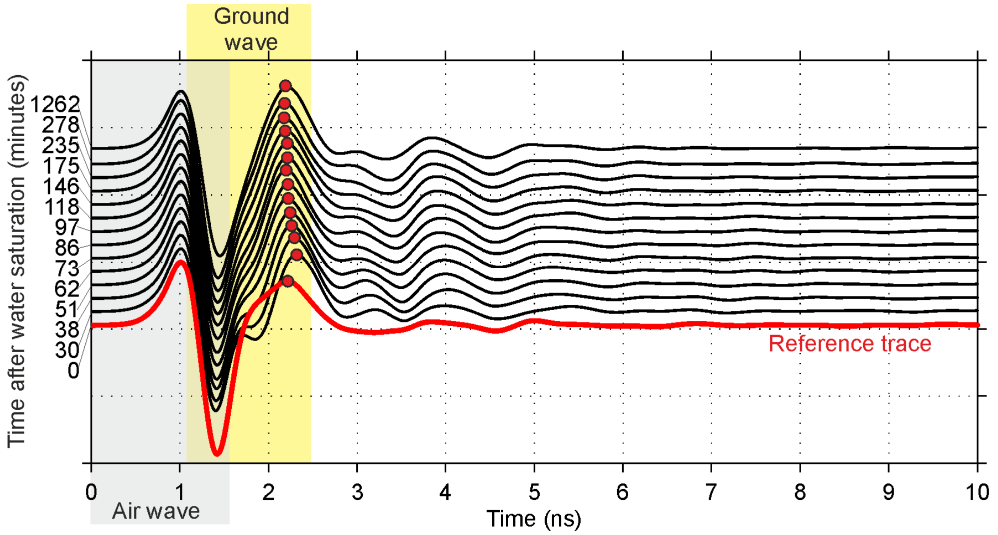

Fig. 4. The result of radargram averaging for each GPR measurment. Red curve (Reference trace) indicates measurement for dry soil. Red dot indicates the time of maximum amplitude observed in ground wave time-window.

4 Results and analysis

In Figure 5 and 6 GPR ground wave parameters changes are presented for different time span after irrigation. In Figure 5 arrival times of maximum amplitude observed in ground wave time-window are presented. The highest delay time is noticed for first measurement i.e. 30 minutes after irrigation. This delay progressively vanishes after next 40 minutes. Probably water infiltrated to the ground and/or evaporated. From observation at 73 minute to the last measurement, delay times have similar values.

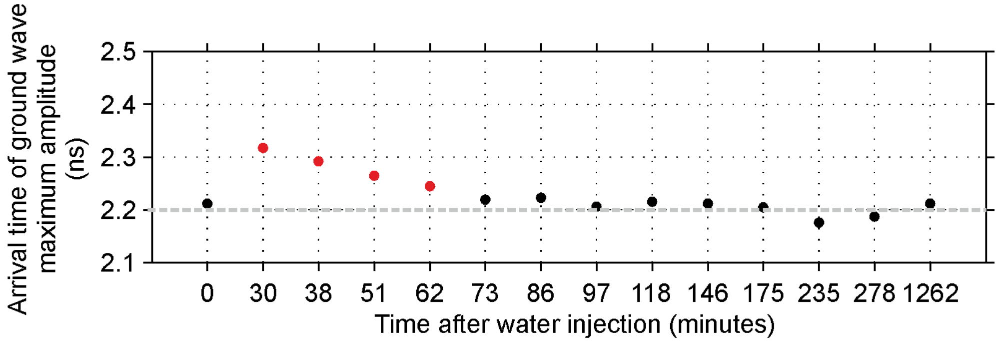

Fig. 5. Arrival times of maximum amplitude for ground wave time window. Time delays after water irrigation are noticed (red dots).

In figure 6 PSD for 14 measurements are shown. PSD was computed for ground wave time window. Frequency and PSD values decrease after water irrigation. These parameters are similar to those for dry soil after measurement at 118 minute.

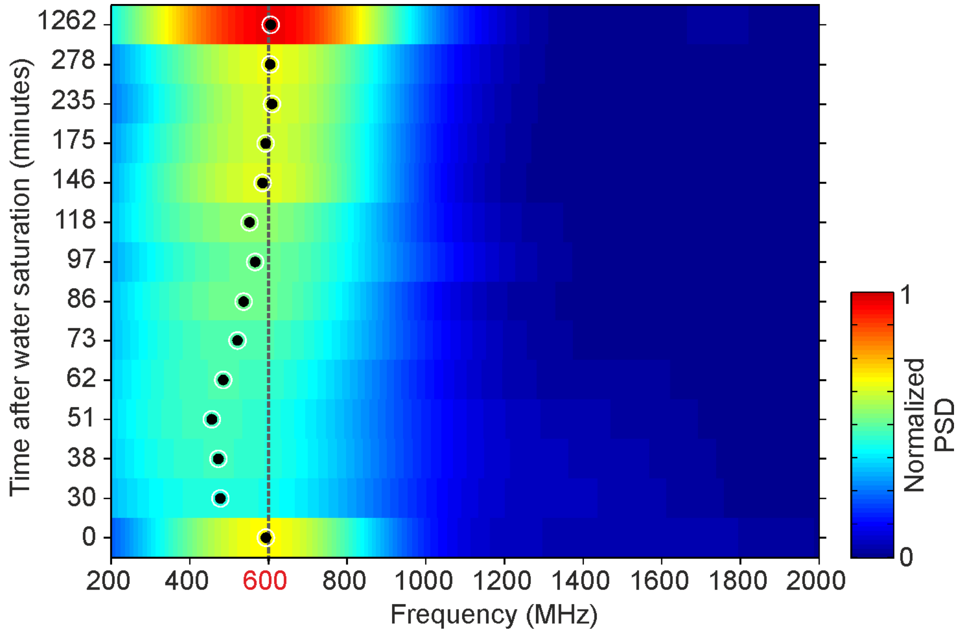

Fig. 6. Power spectrum density for every averaged trace. Black dot denotes maximum value on the PSD.

5 Conclusion

The paper has shown usefulness of using single-offset GPR antenna to monitor soil moisture. Measured parameters are relative and can't be directly connected with water content. However, in case of farmland where soil ingredients don't change significantly, one can determine empirical relation between these parameters and water content by using laboratory test. Future work on this project will attempt to further use single-offset GPR in determination of water content for agricultural purposes.

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